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Modeling Relativistic Nuclear Collisions

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Abstract

Modeling Ultra-Relativistic Heavy Ion Collisions at RHIC and LHC energies using a Multi Module Model is presented. The first Module is the Effective String Rope Model for the calculation of the initial stages of the reaction; the output of this module is used as the initial state for the subsequent one-fluid hydrodynamical calculation module. It is shown that such an initial state leads to the creation of the third flow component. The hydrodynamical evolution of the energy density distribution is

presented for RHIC energies. The final module describing the Freeze Out and Hadronization is also discussed.

The realistic, and detailed description of an energetic heavy ion reaction requires a Multi Module Model, where the different stages of the reaction are each described with a suitable theoretical approach. It is important that these Modules are coupled to each other correctly: on the interface, which is a three dimensional hyper-surface in space-time, all conservation laws should be satisfied and entropy should not decrease. These matching conditions were worked out and studied for the matching at FO in detail in Refs. [1]. Fluid dynamical models are widely used to describe ultra-relativistic

Fluid dynamical models are widely used to describe ultra-relativistic heavy ion collisions. Their advantage is that one can vary flexibly the Equation of State (EoS) of the matter and test its consequences on the reaction dynamics and the outcome. For example, the only models which may handle the supercooled QGP are hydrodynamical models with a corresponding EoS. In energetic collisions of large heavy ions, especially if a Quark-Gluon Plasma (QGP) is formed in the collision, one-fluid dynamics is a valid and good description for the intermediate stages of the reaction. Here, interactions are strong and frequent, so that other models, (e.g. transport models, string models, etc., that assume binary collisions, with free propagation of constituents between collisions) have limited validity.

On the other hand, the initial and final, Freeze-Out (FO), stages of the reaction are outside the domain of applicability of the fluid dynamical model. After hadronization and FO, the matter is already dilute and can be described well with kinetic models. The initial stages are the most problematic. None of the theoretical models on the physics market can unambiguously describe the initial stages (see for example [2, 3] for discussion).

Thus, since we can not unambiguously describe the initial stages of relativistic heavy ion collisions in microscopic models, we have to use some phenomenological models. There are two phe-

nomenological models, which are most frequently discussed in the literature - the Landau and the Bjorken scenarios. These models describe two extreme cases - complete stopping or complete transparency, respectively. Nowadays, experiments have entered the region where the Bjorken model is expected to be applicable, but there is no clear and unambiguous confirmation that experiments follow this scenario. The preliminary experimental results from RHIC do not show transparency - most particle multiplicities (except maybe the most central collisions) do not show a dip in the rapidity spectra, but rather a plateau around mid rapidity [6, 7], which is a sign of strong stopping. Furthermore, very strong elliptic flow has been measured, which shows a clear peak around mid rapidity [6, 9]. To build such a strong elliptic flow, strong stopping and momentum equilibration are required. Also the \bar{p}/p ratio at mid rapidity measured at RHIC [10, 11] (preliminary) is still far from 1, which tells us that the middle region is not baryonfree.

Our goal is to build a Multi Module Model for ultra-relativistic heavy ion collisions valid for RHIC and LHC energies, and maybe for the most energetic SPS collisions. In the present work only the first step is done - a Two Module Model [3, 4] - but a very important one, since the Effective String Rope Model (ESRM) [2, 3] has been developed for the most problematic module - the module describing the initial stages of collisions.

We describe the initial state with the ESRM; then the hydrodynamical evolution with a QGP EoS is used for the intermediate state. The hydrodynamical calculations are performed with the Los Alamos Particle-in-Cell (PIC) one fluid code [13, 14]. The hydro evolution stops at the FO hypersurface. We present a version of the code assuming that FO (simultaneous chemical and thermal) happens on the simplified toothed hypersurface, where its normal vector, $d\sigma^\mu$, is parallel to the flow velocity for every cell. On average this hypersurface approximates the constant time hypersurface. Therefore the flow velocity does not change during the FO process, and the calculations can be done in local rest frame of the matter. Such a surface is also completely timelike; this allows

us to avoid the problems discussed in Refs. [1].

The EoS presently used in the code was used and presented in Ref. [13]. This phenomenological phase transition model A) takes the phenomenological EoS for hadronic matter in a simple form, which nevertheless allows one to check different parameterizations discussed in the literature; B) uses the Bag model EoS to describe QGP; C) creates a complete EoS, containing pure phases and a region where they coexist, by the Maxwell construction.

The reader may notice that the model is still in a formative stage and a lot of further work remains necessary. We are not yet ready to present the quantitative calculations to be compared with data. Nevertheless we present some preliminary results. First of all, the flow component, v_1 , as a function of rapidity, y , is presented in Fig. 1, to show that our expectation that the model will generate a third flow component (Refs. [2]) is reasonable [3, 4]. Our initial state generated by the ESRM indeed produces a strong antiflow in semi-central collisions. The directed v_1 component appears to be very small, as expected for RHIC energies (for example [8]). The peaks in v_1 (actually v_3) around $y = \pm 0.3$ look very high, but this is typical for calculations without thermal smearing [15]. Including thermal smearing will lead to smaller and wider peaks.

We also present the evolution of the energy density distribution, $e(r, t)$, during the hydrodynamic expansion in Fig. 2 (notice that $t = 0$ corresponds to the moment then we start hydro description, i.e. 3.5 fm/c after the collision). We can see the development of the small but very dense, shock-like domains at the intermediate stages. This effect, at least to some extent, is due to numerical artifacts. The PIC method has a well-known defect called 'ringing' or marker-clustering [16]. It is called this way because early calculations in two dimensions resulted in density distributions that looked similar to the vibration patterns in sound vibrations - areas of higher and lower densities [16]. In this particular case, however, these shock-like domains influence the details of the forward/backwards dynamics only and should not influence the observables. Advanced algorithms that mitigate this

effect are being implemented in the code.

To evaluate the observables a third, Freeze Out module is going to be attached to the model. Here the widely used Cooper-Frye model should be essentially improved and modified. First of all conservation laws and the requirement of increasing entropy should be enforced in the module. In addition, particularly for freeze out across space-like hypersurfaces, realistic, non-equilibrium post freeze out phase space distributions will have to be used to avoid negative contributions occurring in the naive use of the Cooper-Frye model [1, 3].

References

- [1] Cs. Anderlik et al., *Phys. Rev. C* **59** (1999) 388, (nucl-th/9808024); *Phys. Rev. C* **59** (1999) 3309, (nucl-th/9806004); *Phys. Lett. B* **459** (1999) 33, (nucl-th/9905054); V.K. Magas et al., *Heavy Ion Phys.* **9** (1999) 193, (nucl-th/9903045); *Nucl. Phys. A* **661** (1999) 596, (nucl-th/0001049).
- [2] V. Magas, L.P. Csernai, D. Strottman, *Phys. Rev. C* **64** (2001) 014901, (hep-ph/0010307); Proceedings of the New Trends in High-Energy Physics, Yalta (Crimea), Ukraine, May 27 - June 4, 2000, p. 93, (nucl-th/0009049); Proceedings of the ISMD 2000, Tihany, Lake Balaton, Hungary, October 9-15, 2000, p. 523, (hep-ph/0101125); L.P. Csernai, Cs. Anderlik, V.K. Magas, Proceedings of the Symposium on Fundamental Issues in Elementary Matter, Bad Honnef, Germany, September 25-29, 2000, p. 77, (nucl-th/0010023).
- [3] V.K. Magas, PhD Thesis, Aug 2001, University of Bergen, Norway.
- [4] V.K. Magas, L.P. Csernai and D. Strottman, Proceedings of the New Trend in High-Energy Physics, Yalta, Crimea, Ukraine, September 22-29, 2001 - in press.

- [5] M. Gyulassy, L.P. Csernai, *Nucl. Phys. A* **460** (1986) 723.
- [6] P. Steinberg, nucl-ex/0104006; R. Snellings, A. Drees, talks at the Quark Matter 2001, Stony Brook, NY, USA, January 15-20, 2001.
- [7] STAR Collaboration, *Phys. Rev. Lett.* **87** (2001) 112303, (nucl-ex/0106004).
- [8] P. Huovinen, talk at the School on Relativistic Heavy Ion Physics & Hard Probes Collaboration Meeting, Copenhagen, Denmark, May 14-18, 2001.
- [9] PHENIX Collaboration, nucl-ex/0105003; PHOBOS Collaboration, nucl-ex/0105015; STAR Collaboration, *Phys. Rev. Lett.* **86** (2001) 401, (nucl-ex/0009011); nucl-ex/0107003.
- [10] F. Videbaek, talk at the Quark Matter 2001, Stony Brook, NY, USA, January 15-20, 2001.
- [11] C. Adler, et al., (STAR Collaboration), *Phys. Rev. Lett.* **86** (2001) 4778. (nucl-ex/0104022)
- [12] L.P. Csernai, D. Röhrich, *Phys. Lett. B* **458** (1999) 454. (nucl-th/9908034)
- [13] A.K. Holme, E.F. Staubo, L.P. Csernai, E. Osnes, D. Strottman, *Phys. Rev. D* **40** (1989) 3735.
- [14] E.F. Staubo et al., *Phys. Lett. B* **229** (1989) 351; *Phys. Scripta T* **32** (1990) 190; N.S. Amelin et al., *Phys. Lett. B* **261** (1991) 352; *Phys. Rev. Lett.* **67** (1991) 1523; *Nucl. Phys. A* **544** (1992) 463; L.V. Bravina et al., *Nucl. Phys. A* **566** (1994) 461; *Phys. Rev. C* **50** (1994) 2161.
- [15] H. Stöcker et al., *Phys. Rev. Lett.* **47** (1981) 1807.
- [16] J. U. Brackbill, *J. Comput. Phys.* **75**, (1988) 469.
- [17] T. Hirano, nucl-th/0108004.

Figure 1: Preliminary results of Two Module Model calculations for v_1 vs rapidity, y . Au+Au collision at $\varepsilon_0 = 65 \text{ GeV}/\text{nucl}$ for different impact parameters. Initial state was generated with $A = 0.065$, $\tau = 3.5 \text{ fm}/c$ (see [2, 3] for details).

Figure 2: Preliminary results of Two Module Model calculations for energy density distribution in the reaction plane. Au+Au collision at $\varepsilon_0 = 65 \text{ GeV}/\text{nucl}$, $b = 0.1 \cdot 2R_{Au}$ for different moments of time; initial state was generated with $A = 0.08$, $\tau = 3.5 \text{ fm}/c$ (see [2, 3] for details).



